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IMPROVING YBCO COATED CONDUCTORS FOR APPLICATIONS (POSTPRINT)

P.N. Barnes, B.C. Harrison, J.W. Kell, and G.A. Levin

Mechanical Energy Conversion Branch
Energy/Power/Thermal Division

M.D. Sumption

The Ohio State University

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P.N. Barnes, B.C. Harrison, J.W. Kell, and G.A. Levin (AFRL/RZPG)
M.D. Sumption (The Ohio State University)

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14. ABSTRACT
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IMPROVING YBCO COATED CONDUCTORS FOR APPLICATIONS

P. N. Barnes[1], B. C. Harrison[1], J. W. Kell[1],
G. A. Levin[1] and M. D. Sumption[2]
[1]Air Force Research Laboratory
Wright-Patterson AFB, Ohio 45433, USA

[2]LASM, The Ohio State University
Columbus, OH 43210, USA

ABSTRACT

Superconducting power devices made of high temperature superconductors (HTS) can enable megawatt-class power systems which are lighter in weight and smaller in size than their conventional counterparts. The YBCO coated conductor is expected to be the premiere HTS conductor in making these systems. With advances in YBCO deposition techniques and the establishment of reel-to-reel processing, new research should address enhancement of the YBCO coated conductor's performance. These improvements in the YBCO conductor must include maintaining high critical current densities in fields of a few tesla and minimizing ac losses. This paper first discusses a current sharing scheme in the multifilamentary YBCO conductor to circumvent filamentary breakage. Also, a method for providing magnetic flux pinning to increase the current capacity of the YBCO conductor is outlined using minute additions of rare earth dopants.

KEYWORDS: YBCO Conductor, AC Loss, Flux Pinning, Superconducting Machines.
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INTRODUCTION

A variety of future military systems will require large amounts of power at the multi-megawatt level [1,2]. Since these are on mobile platforms, the power subsystems must often be packaged in a limited space and within strict weight limits. Because of these considerations, high temperature superconducting (HTS) machinery such as generators,

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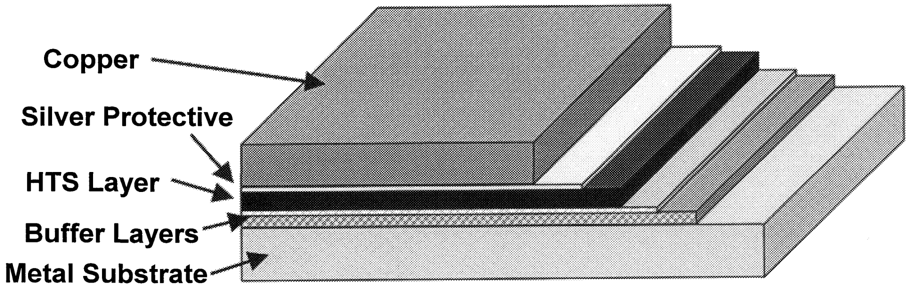


FIGURE 1. The basic YBCO coated conductor architecture is depicted above with the typically accompanying layers.

motors, and transformers are being developed to address these power concerns. HTS conductors make the development of these HTS power devices possible. As such, a significant amount of development has been undertaken for the basic HTS conductor, especially more recently the $YBa_2Cu_3O_{7-x}$ or YBCO coated conductor. YBCO coated conductors have demonstrated great potential, now being available in lengths of 100 m or more. Figure 1 shows the basic architecture of the YBCO coated conductor.

With the advancement mentioned above and the establishment of continuous processing, new research should address additional improvements to the YBCO coated conductor's performance, although a thorough assessment of the relevant remaining issues for HTS conductors may be necessary for it's use in machines[1,3]. Enhancements to the basic YBCO coated conductor can more readily promote the use of HTS power devices and allow additional reductions in size and weight of already compact power systems. Improvements to the YBCO coated conductor must among other things focus on maintaining high critical current densities in fields of a few tesla as well as keeping ac losses to a minimum. The following sections discuss two possible conductor enhancements: one being an improvement to the ac-tolerant version of the conductor and the other being a potential flux pinning mechanism.

HTS Synchronous Machinery

When considering enhancement of the basic YBCO conductor, an understanding of the eventual superconducting application is necessary. This is particularly important for rotating machinery. Basic ac synchronous superconducting generators and motors can be divided into two basic types. The first is the standard hybrid design in which only the field windings of the rotor use superconductors. The armature is conventional using copper windings. In the rotor, the superconductor will experience mostly a dc field, except for ac losses due to asynchronous feedback. Typically, shielding is used to minimize these losses as opposed to making use of a more ac-tolerant version of the HTS wire. Efficiency is higher than conventional counterparts since the superconducting field windings have an essentially zero DC resistance. However, there are key issues associated with isolating the rotating cryogenic vessel from the room temperature stator and the required cryogenic cooling connections to the spinning rotor.

The other classification of HTS rotating machines is the fully superconducting version, or all-cryogenic. When the superconducting generator or motor is fully superconducting, the field and armature windings are both made with superconducting wire. As such, the stator and the rotor jointly reside in an outer cryogenic jacket. Since the armature windings experience a fairly large alternating magnetic field, the ac loss contribution of the armature is significant. AC losses in the armature include not only hysteretic losses in the superconductor, but normal metal effects such as eddy currents, ferromagnetic substrate contributions, and eddy coupling current losses. Only a strictly ac-tolerant version of the YBCO coated conductor could be used which significantly minimizes these effects. An all-cryogenic design would be the ideal solution, if possible. This type of superconducting generator has a much simpler design and potential for greater efficiency and higher reliability.

YBCO CONDUCTOR ENHANCEMENTS

AC Loss Minimization

Minimizing the ac losses in coated conductors is critical for its use in ac applications, especially in armature windings. In an all-cryogenic, high speed, rotating machine, the frequency of operation is significantly greater (hundreds of Hz), making this an absolutely critical issue [1,4]. Conductors must be designed to minimize these losses in order that the size and weight gains realized with the use of superconducting windings are not diminished by the need for a larger cooling system. With a sufficiently ac-tolerant YBCO conductor, unshielded rotor windings are possible, too. To consider the applicability of ac-tolerant HTS wire in superconducting generators, it is necessary to determine general YBCO conductor ac requirements. Recently, initial efforts have been established to determine the impact of ac losses in the YBCO coated conductors for generator applications [5].

The hysteresis loss in the superconductor is proportional to the width of the YBCO film that is perpendicular to the applied field. Thus, large losses can occur when the magnetic field is perpendicular to the tape. These losses can be reduced by filamentation of the HTS layer [6-8]. In armature windings, this may require the filaments to be quite fine [9]. In this case, it is not unreasonable that a blockage may occur somewhere along the length of the filament, either due to mechanical strain on the ac conductor, localized heating, or small defects arising during manufacturing or handling of the conductor which might otherwise not occur in the wide tape or even in wider filaments. When this occurs the entire filament is no longer capable of carrying any current, where the interfilamentary connection is completely insulating. It is quite possible that this could occur to several of the filaments if the conductor length is rather long making a significant fraction of the filaments to be incapable of carrying current, seriously reducing the current carrying capacity of the YBCO conductor.

Creating an ac-tolerant multifilamentary YBCO tape while still allowing for some level of current sharing may avoid this issue, while still maintaining low losses [10]. In higher frequency applications this can be troublesome where interfilamentary connections result in power loss which increases quadratically with frequency. Therefore, the use of

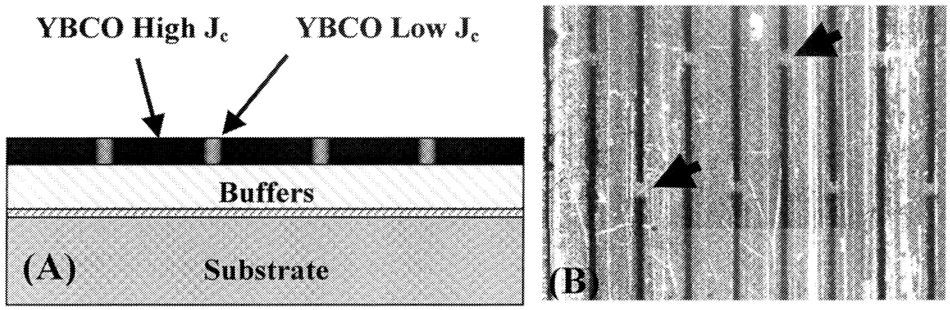


FIGURE 2. Interfilamentary current sharing by weak superconducting connections between the filaments are depicted above: (A) cross-section of a homogeneous lower J_c region separating the filaments, or (B) planar view of small superconducting bridges dispersed along a resistive barrier.

metallic enabled current sharing in filamented YBCO conductors is not possible for high frequency
(100-1000 Hz) applications. Indeed, this is one of the primary factors that has generally precluded the use of superconducting wire in armature windings. The power loss due to superconducting currents, on the other hand, increases only linearly with frequency. Thus, it is possible to conceive of a low level superconducting connection which will enable the current sharing, while still maintaining low ac losses. This should allow the construction of finely filamented YBCO coated conductors with low ac loss, but with maximal transport properties. It is important to realize that the HTS filaments need only be adequately separated along the entire length of the HTS conductor which places an upper limit to the amount of possible current flow per unit length between the filaments.

It may be useful then in the ac-tolerant version of the YBCO conductor to have interfilamentary current sharing by weak superconducting connections between the filaments either by a homogeneous lower J_c region separating the filaments or by small superconducting bridges dispersed along a resistive barrier [10-12]. Figure 2 depicts these two possibilities. Placement of the bridges must be such that they allow the current in a broken filament to circumvent the blockage, are sufficiently spaced to maintain high reductions in the hysteresis loss, and give consideration to any associated twisting of the conductor for magnetic field penetration [13]. In addition, for a useful scheme, the degraded regions must not be localized--all filaments may be degraded, but the degradation is occasional and random allowing the current to redistribute to all other filaments in the cross section over a given sharing length. As such, even with 100% blockage of all individual filaments, the overall critical current of the conductor would only be slightly degraded over the conductor's cross-section.

The second current sharing scheme mentioned above was investigated where coated conductors were laser etched to remove YBCO to create multiple filaments with small YBCO interconnects. Figure 3 shows the magnetization loops measured for a set of these coated conductor samples with various striation patterns taken at a frequency of 200Hz. The patterns used are depicted in Figure 3C, where the interconnects were spaced to achieve a particular value of α where α is the ratio of the theoretical current carried along the length of the conductor to the theoretical current carried along the width. The hysteresis loss, which is the integral of the magnetization over one cycle, is diminished for the striated

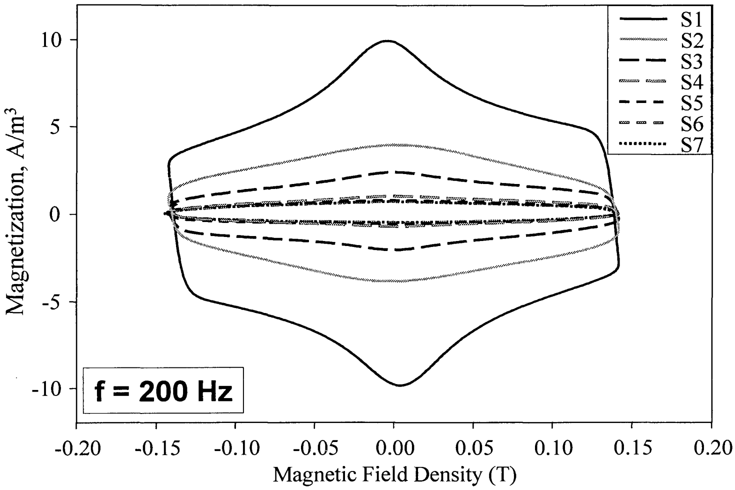
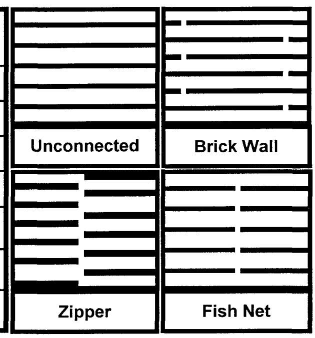


FIGURE 3. (A) Magnetization loops measured for a set of coated conductors with different striation patterns. (B) Describes the type of striation and the hysteric loss in each conductor in relation to an unstriated sample. (C) Diagrams of each of the striation patterns.

Sample	Striation Pattern	Number of Striations	α	Normalized Loss
S1	Unstriated	1	1	100%
S2	Brick Wall	20	15	46%
S3	Zipper	10	40	14%
S4	Unconnected	20	∞	9.6%
S5	Unconnected	40	∞	8.3%
S6	Brick Wall	40	400	7%
S7	Fish Net	40	400	7%



conductors. The interconnect pattern was found to have little affect on the hysteresis loss. The most important factor was found to be α. Losses for conductors with values of α at 400 were found to be less than those of samples with completely independent filaments. Therefore it is possible that interfilamentary connections can be used while still optimally reducing the hysteretic losses.

Magnetic Flux Pinning

One of the critical issues for enabling wide-spread use of superconducting generators is increasing the engineering current density of the YBCO conductor to the level that higher operating temperatures are practical. One way to do this is to establish higher critical currents in the YBCO layer. This can be accomplished by either making thicker YBCO films or improving the pinning characteristics of the YBCO layer. In the area of pinning

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enhancement, one method recently discovered by Haugan et al. is the inclusion of a nanoparticulate dispersion into the superconducting phase of YBCO [14,15]. In this particular case, the nanoparticles were introduced by a composite multilayer structure which was created by growing the YBCO layer and the nanoparticles by multiple, consecutive pulsed laser depositions using the respective targets. This allowed improvements in the film's critical current density by 3 – 5 times that of plain YBCO at applied fields of a few tesla over a range of temperatures. Also being considered for improvement to the YBCO coated conductor is the effect of chemical composition variations on the flux pinning and physical properties of $(Y,RE)_{1+x}Ba_{2-x}Cu_3O_{7-\delta}$ superconductors [16,17].

An alternative method for providing magnetic flux pinning to increase the current capacity of the YBCO conductor is the use of minute additions of rare earth dopants, dopants that tend to degrade the superconductors performance. The most important feature of these dopants (such as Tb and Ce) are that at typical concentrations of 10% or greater for rare earth replacement of Y in YBCO, these elements are detrimental to the in-field current density of the resultant film. Prior work has demonstrated the degrading nature of these elements as inclusions into the Y123 structure [18]. However, when concentrations are reduced to smaller proportions, enhancement of J_c is possible [19]. Figure 4 shows the pinning force brought about by pinning centers contained within 0.1% and 1% Tb and 0.1% Ce doped YBCO films at 77K. In each case the in-field performance exceeds that of pure YBCO, with further performance enhancements at 65K. In our previous work [19] samples of 0.1% Tb and Ce doped samples showed no definite improvement over pure YBCO at 77K, however, additional samples indicate there can be improvement with both. However, for an addition of 1% Ce the pinning force was still found to be nearly equivalent to pure YBCO. The difference between the minor Tb concentration and the minor Ce concentration can be ascribed to the degrading effects of Ce on T_c, whereas Tb does not produce such reductions in T_c.

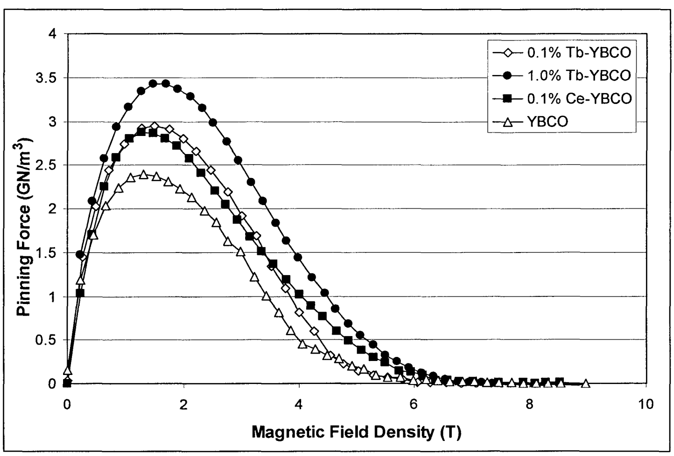

FIGURE 4. Pinning force of doped and pure YBCO films in a 0-9T magnetic field applied parallel to the c-axis of the films at 77K. All films were deposited on single crystal LAO substrates.

Perhaps the greater difficulty of this technique for introducing pinning sites into the YBCO is obtaining a well dispersed mixture of < 1% Tb or Ce. If possible, this method of minute additions is likely to be more readily incorporated into standard deposition techniques for YBCO.

Other Enhancement Considerations

Although ac-tolerance and increased critical currents were discussed above (particularly pinning), this does not mean that these are the only necessary enhancements to the YBCO coated conductor. HTS wire, which operates at substantially higher temperatures than LTS wire, has a much greater intrinsic stability margin. Even so, quenching of HTS magnets and coils are possible. Because of the possibility of quench, the conductors must be protected in the case that a quench does occur, or the coil windings can be irreparably damaged. The level and type of stabilizer to be added should allow for proper protection. Additional stabilizer is unwanted because it will decrease the engineering current density. Also, extra metallic stabilizer lowers the voltage produced in a quench, making detection more difficult. Thus, the choice of stabilizer level is a tradeoff between detection and protection. The dielectric insulation of the YBCO coated conductor is also relevant to this issue. The insulation should highly resistive electrically, but highly conductive thermally during normal operation. Materials used in the YBCO coated conductor architecture must consider mechanical stress as well thermal cycling, field cycling, and mechanical cycling. Thermal management distribution issues should include cryogenic to room temperature thermal connectivity as well.

CONCLUSIONS

With advances in YBCO coated conductor processing, research should now begin to focus on performance enhancement of the YBCO conductor. These enhancements include a more ac-tolerant version of the conductor and improved current capacity such as by flux pinning mechanisms. In making an ac-tolerant version of the YBCO conductor via a multifilamentary structure, consideration must be given to interfilamentary current sharing schemes when fine filaments are used. Superconducting linkage to enabled current sharing allows breakage in the filaments to be circumvented while still allowing substantial reduction in the hysteretic loss. With respect to flux pinning, minute additions of rare earths, which are typically considered degrading at higher levels, can offer substantial improvement to the YBCO critical current capacity. Minor additions of Tb and Ce are examples of this type. Decreasing the quantity of Tb to 1% or less appears to produce enhanced pinning characteristics of the resulting films especially at higher fields. For Ce, this is at ~0.1% additions at 65 K.

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